

UNCLASSIFIED

AD 259 074

*Reproduced
by the*

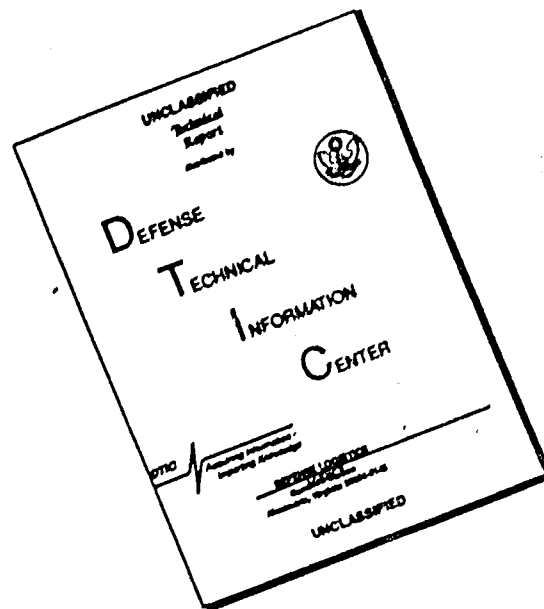
ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

FOR OFFICIAL USE ONLY

MAILED FOR

19 APR 1961

U. S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

Aviation Medical Acceleration Laboratory

NADC-MA-6108

19 April 1961

The Measurement of Bioclimatological
Heat Exchange

Bureau of Medicine and Surgery
Subtask MR005.15-2002.1 Report No. 24



259 074

CATALOGED BY ASTIA
AS ADMO

U. S. NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE, PENNSYLVANIA

Aviation Medical Acceleration Laboratory

NADC-MA-6108

19 April 1961

The Measurement of Bioclimatological
Heat Exchange

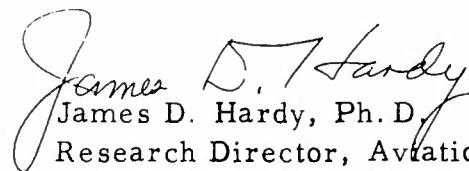
Bureau of Medicine and Surgery
Subtask MR005.15-2002.1 Report No. 24

Prepared by:



Alice M. Stoll

Approved by:



James D. Hardy, Ph. D.
Research Director, Aviation Medical
Acceleration Laboratory, and Professor
of Physiology, University of Pennsylvania

Approved by:



F. K. Smith, Captain, MC, USN
Director
Aviation Medical Acceleration Laboratory

SUMMARY

Determinations of heat exchange between man and his environment require measurements of the radiant temperatures of both man and his surroundings and of any incident solar radiation. The most recent instruments developed specifically to meet these needs are the wide range Thermistor Radiometer and the Panradiometer. Used simultaneously, these two instruments provide all necessary radiation measurements. The Thermistor Radiometer measures a wide range of environmental radiant temperature in extremes of naturally occurring ambient temperature as well as skin temperature. It consists essentially of a bridge composed of four flake thermistors, two exposed to the area to be assessed and two adjacent to the exposed flakes but hidden by the rim of the collecting cone mounted in front of the thermistors. The instrument is capable of an accuracy of $\pm 0.05^{\circ}\text{C}$ and has been used in ambients of -50°C to $+30^{\circ}\text{C}$ for the measurement of radiant temperatures within $\pm 135^{\circ}\text{C}$ of the ambient. The Panradiometer provides measurements of net heat exchange between man and his environment together with a description of the environment in terms of solar radiation, average radiant temperature of the surroundings in sun and in shade, and wind temperature and velocity, all in absolute physical units suitable for computations of the heat load on the individual. The design of this instrument takes advantage of the fact that about 99% of the solar radiation lies at wavelengths less than 3μ and about the same proportion of the radiation from man to his surroundings lies at wavelengths longer than 4μ . Thus, by utilization of heat detectors of different emissivities, the high temperature radiation is separated from the low temperature radiation. In brief, the instrument embodies three detectors which consist of hollow spheres equipped with thermocouples for measuring their temperatures and internal heaters for adjusting their temperatures. When all spheres are brought to the temperature of the warmest sphere in a given environment, the amount of heat required to maintain this balance is an accurate measure of the environmental heat exchange from which various temperature and radiation terms are derived. Wind temperature and velocity are measured by means of a fourth sphere. A few representative natural environments have been evaluated with these two instruments. Illustrative of the sort of information derivable are the comparisons of radiant heat loads and operative temperatures measured in midsummer in the hot desert of Death Valley, in the arid Alaskan interior at Fairbanks, and in the heart of New York City. It is seen that the main difference between a stressfully hot environment and a thermally comfortable one was not due to a decreased solar intensity in Alaska, as might be supposed, for the Panradiometer measurements showed that some of the highest solar intensities occurred there. Instead, the cooler environment, despite equivalent solar radiation, was shown by the Thermistor

Radiometer measurements to be due primarily to the cool sky which constituted a sink for the radiation from the earth and the man, contributing both directly and indirectly to reduction of the radiant heat load. In the indoor environment, measurements of radiant heat load made with these instruments provided concrete evidence of the need for air-conditioning in operating rooms for infants and small children.

LIST OF FIGURES (cont'd)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8	Panradiometer measurements of direct solar radiation compared with direct measurements	13
9	Selected data from three localities to show interaction of bioclimatological components	18

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
I	Bioclimatological data from three localities	17
II	Measurements of radiant heat load and operative temperature indoors under operating lights	21

TABLE OF CONTENTS

	<u>Page</u>
SUMMARY	ii
INTRODUCTION	1
INSTRUMENTS AND METHODS	1
APPLICATIONS	14
Outdoors	14
Indoors	19
SUMMARY OF RESULTS	20
REFERENCES	23

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Thermistor Radiometer thermal receivers	3
2	Thermistor Radiometer calibration curves	4
3	Thermistor Radiometer	5
4	Basic receivers of Panradiometer	7
5	Panradiometer — receivers and control panel.....	8
6	Panradiometer measurements of wall temperature compared with thermocouple measurements	11
7	Panradiometer measurements of the radiant tem- perature of the surroundings compared with direct survey	12

INTRODUCTION

In this day of the rapidly growing dictionary, perhaps it would be well to define immediately exactly what is meant by "bioclimatological heat exchange".

To begin with, climate is defined as the average course or condition of the weather at a particular place. Bioclimate is, then, this average course or condition of weather with respect to life, so that one may speak of the bioclimate as being tolerable, beneficial, deleterious, or intolerable depending upon the effect of the climate on living organisms. Bioclimatology is specifically the study of these effects, and bioclimatological heat exchange is the process by which the effects are produced. The measurement of this process requires the quantitation of the effect of individual climatic components in producing heat loss or gain in living creatures. This report, then, deals with the determination of these components and their evaluations in terms of the bioclimate and, particularly, with the instruments developed for this work.

Of the various components, radiation is by far the most difficult to measure. In fact, until the instruments and methods to be described here came into use during the past decade, direct measurements of climatic radiation components in terms of standard physical units had not been accomplished in the outdoor environment. Prior to this time, instruments which gave very useful indices of relative effects including radiation had been used (1,2,3,4,5); methods of combining effects of various climatic components had been worked out in carefully controlled laboratory chambers (6,7,8,9); and various radiation heat exchange balances were computed from measurements of insolation, temperatures of the earth, and pertinent atmospheric data (10,11). Such indirect procedures were limited in usefulness, however, because they failed to provide thermal radiation data in standard physical units directly applicable to the living being exposed in the given surroundings. Results obtained with one instrument could not be compared directly with those obtained with another. Individual elements of the total heat exchange complex could not be extracted to determine their importance in the complex. These shortcomings, then, were the principal reason for the initiation of a new approach in instrumentation and methods of measurement of environmental heat exchange.

INSTRUMENTS AND METHODS

The program was conducted at the Cornell University Medical College, supported in part by the Office of Naval Research and directed

by James D. Hardy. It extended over a period of six years and resulted in the development of new measuring instruments and methods and data representative of a few different types of climatic situations. The instruments developed were the Panradiometer (12) for the separation and measurement of solar and low temperature radiation exchange and convection effects; the Thermoradiometer (13), a modification of the Hardy Dermal Radiometer (14) for the measurement of surface and environmental temperatures; and the Thermistor Radiometer (15), which supplanted the Thermoradiometer by reducing the area viewed in measuring such temperatures and extending the range of ambient operation down to the level of the lowest naturally occurring environmental temperatures.

The Panradiometer and the Thermistor Radiometer provide all the data required for an exhaustive analysis of the radiation and convection characteristics of the environment. With only these two instruments, it is possible to measure direct solar radiation, reflected and scattered solar radiation, the average radiant temperature of the total surroundings, the radiant temperature of the sky and of the ground separately, the air temperature and the wind velocity.

Detailed descriptions of the instruments and their method of use have been published (12, 13, 15). Briefly, the Thermistor Radiometer, the simpler of the two, utilizes four thermistors mounted as shown in Figure 1 and arranged in a bridge circuit. Two thermistors are exposed to the radiation and two are hidden from the radiation by means of the collecting cone. The output of the bridge is amplified and fed to a meter which may be calibrated to suit the user. In Figure 2, calibrations are shown for ranges up to $\pm 135^{\circ}\text{C}$ at ambients from $+20^{\circ}\text{C}$ to -50°C . The discrepancy between the slopes for the same, ΔT above and below zero, is due to the smaller energy exchange which occurs for a given temperature difference at lower temperatures in accordance with the Stefan-Boltzmann law. Thus, the energy exchange between radiators at -50°C and 0°C is twice as large as that for an equal ΔT between radiators at -50°C and -100°C . Over shorter ranges and at higher temperatures, this discrepancy is somewhat less and the slopes of the calibration curves for temperature above and below ambient are more alike.

A photograph of the complete instrument is shown in Figure 3. It is used at least as much for the measurement of skin and surface temperatures as it is for that of environmental temperatures. The operation is simple: the meter is zeroed with the radiometer directed toward the black body standard which is maintained at ambient temperature; the radiometer is then pointed at the surface to be measured and the meter deflection is read

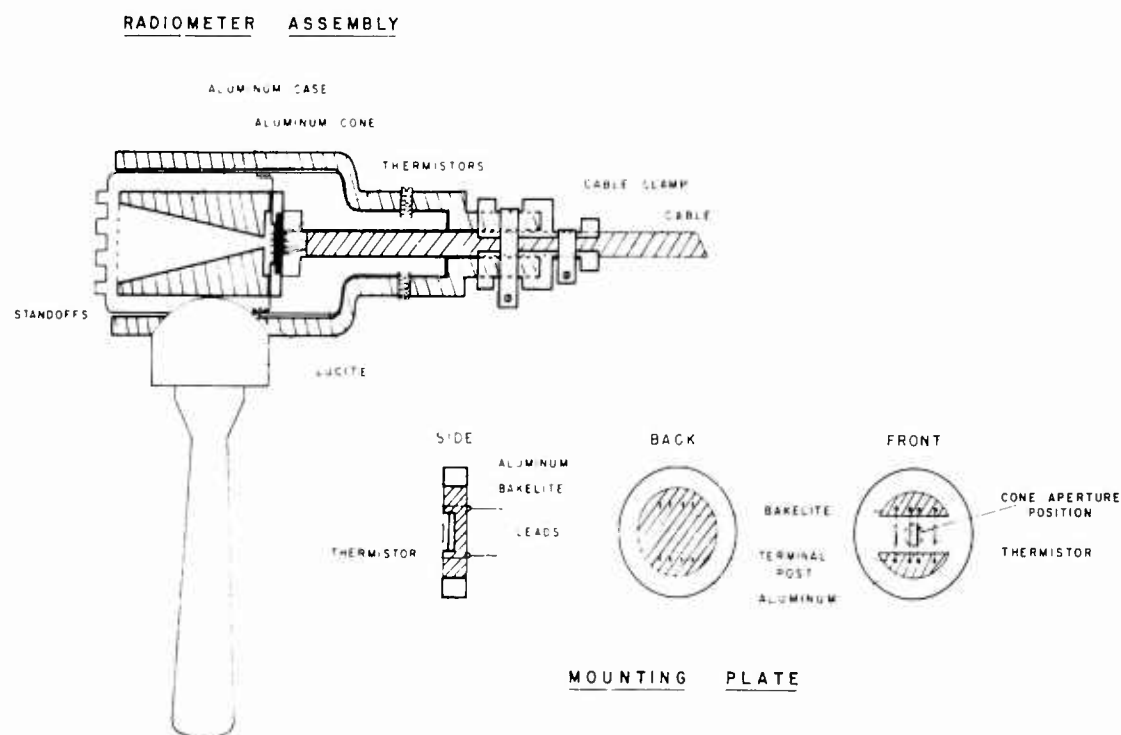


Figure 1. Thermistor Radiometer thermal receivers.

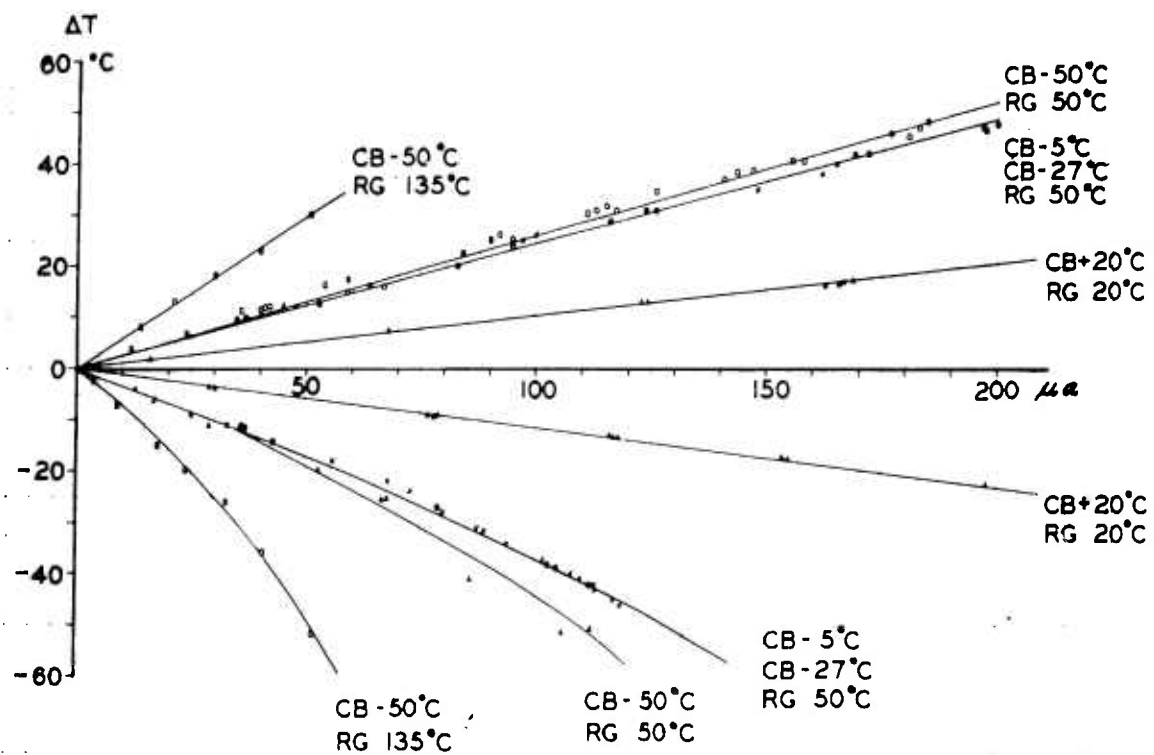


Figure 2. Thermistor Radiometer calibration curves.

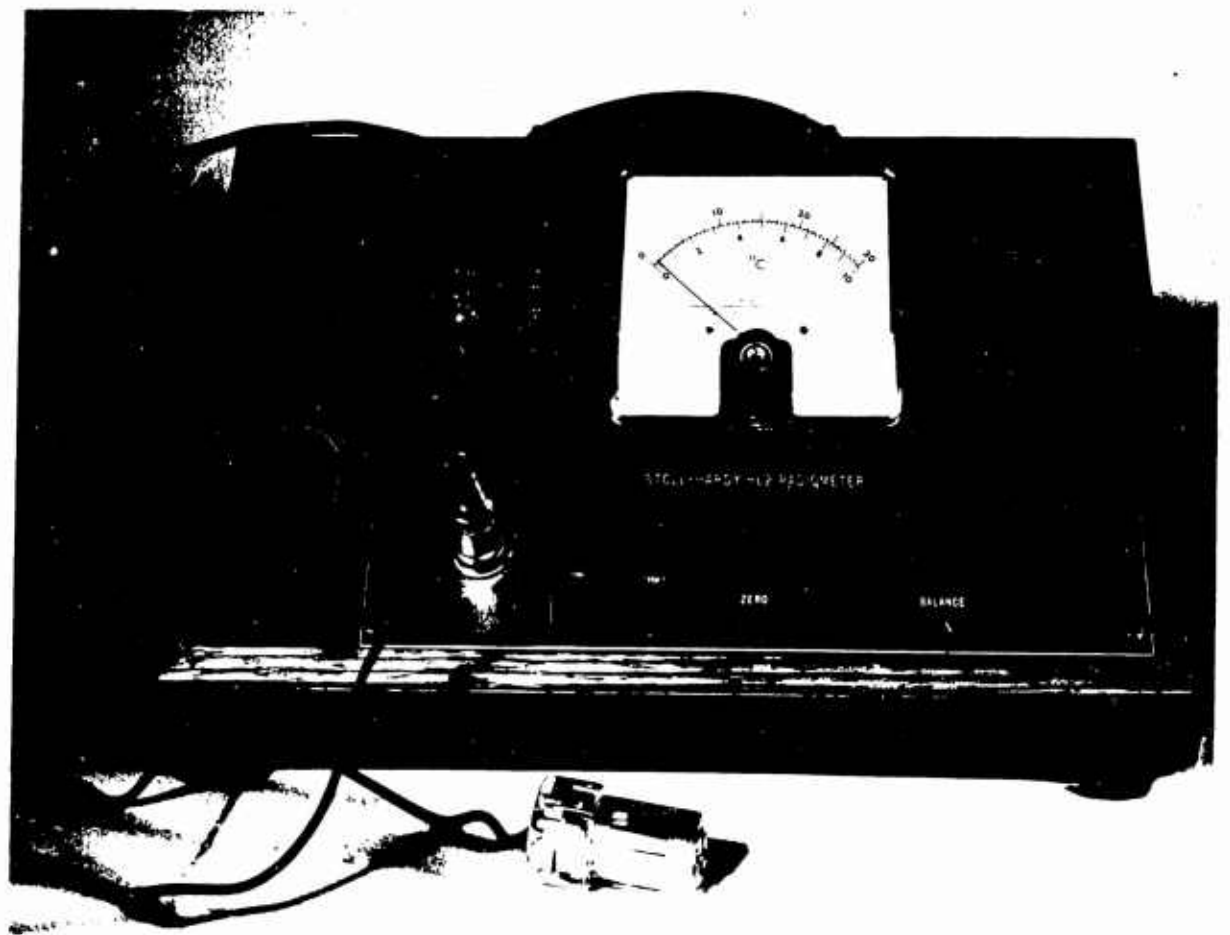


Figure 3. Thermistor Radiometer.

and added to the ambient temperature to obtain the radiant temperature of the observed surface. As the emissivity of the observed surface approaches unity, the radiant temperature so measured approaches the true temperature of the surface. For the human skin, having an emissivity of 0.99 (14), in the infrared, there is no better measure of true temperature than a radiometric one. Similarly, in measurements of the radiant temperature of the ground and terrestrial objects, the emissivity in the infrared is also close to one so that, by suitable corrections for reflected and scattered solar radiation, the temperature of the surroundings may be determined from such simple measurements. The corrections are easily made by repeating each measurement with a glass filter in front of the receivers. The glass absorbs infrared and transmits visible radiation. Thus, the measurement taken through the filter represents the contribution of scattered and reflected solar radiation and may be subtracted from the reading without the filter to yield the radiant temperature of the region surveyed. The detailed method for surveying the total surrounds has been published (13). It consists of temperature measurements at ten points, five in the upper hemisphere N, S, E, W and zenith and five in the lower hemisphere N, S, E, W and nadir. Measurements are made with and without the glass filter, the instrument being held or shielded so that direct radiation from the sun into the radiometer is always avoided. From these measurements, the average temperature of the sky and of the ground may be computed as separate entities. Further computations yield the scattered solar radiation and the reflected solar radiation as separate entities (16). At night, or during complete heavy overcasts, when direct solar radiation is zero, this instrument alone can provide all the radiation and temperature data required to determine the radiant heat exchange between man and his environment.

When solar radiation is present in appreciable amounts, the Pan-radiometer provides all necessary data to determine radiant heat exchange and, in addition, the effect of convective heat loss by virtue of its measurements of air temperature and velocity. The operation of this instrument is based upon the fact that most of the solar radiation reaching the earth lies at wavelengths in the visible and near infrared while the radiation from man to his surroundings lies at wavelengths in the far infrared. Thus, it is possible by selection of heat receivers of appropriate emissivities to separate the high from the low temperature radiations. Figure 4 shows the basic heat receivers of the Panradiometer. These are hollow, chromium-plated silver spheres, 6 1/2 mm in diameter and of identical construction. Each is provided with a thermocouple for measuring its temperature and an internal heating coil for adjusting its temperature. One sphere is painted dull black, one white, and two are highly polished as shown in Figure 5. The emissivity in the infrared and the visible

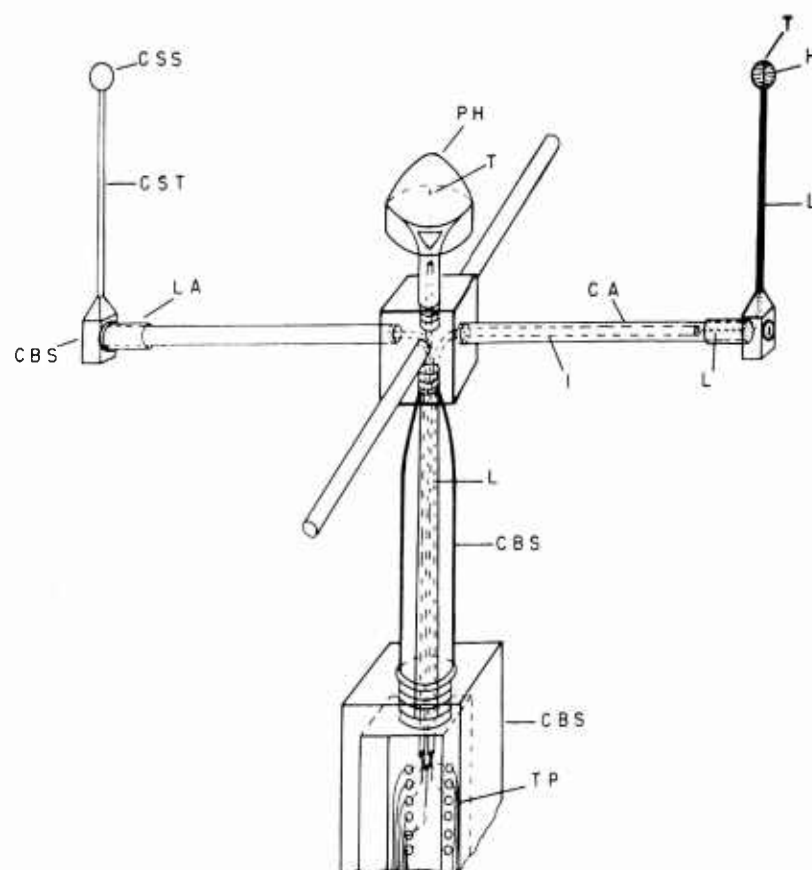


Figure 4. Basic receivers of Panradiometer.

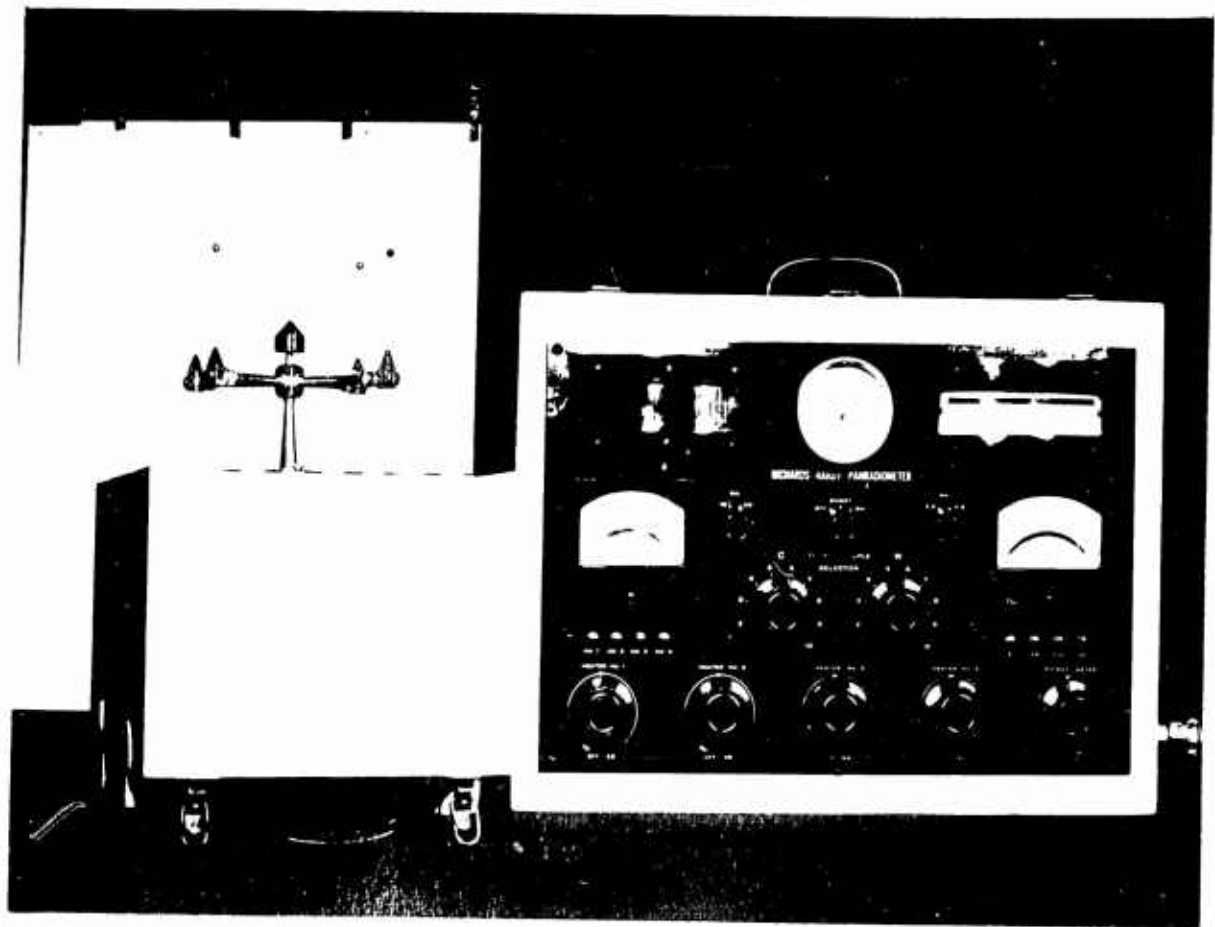


Figure 5. Panradiometer — receivers and control panel.

wavelengths is determined for each sphere. Only three spheres are required for a radiation measurement; the second polished sphere is used as a hot-sphere anemometer. To the right in this figure is seen the instrument panel with selector switches for comparing the temperature of any sphere with that of another, and adjustments for supplying heat to each of the spheres; meters for measuring the heat supplied; a null point galvanometer to indicate when all spheres are at the same temperature and a second galvanometer to indicate wind velocity changes during a measurement. When these spheres are placed in a clear sunny outdoor environment, the black sphere of emissivity, close to 1.0 in both the visible and the infrared range, comes to the highest temperature; the polished sphere, being almost totally reflecting in the visible and only slightly less so in the infrared, becomes only slightly warmer than the ambient air; and the white sphere, which reflects much of the visible radiation and emits strongly in the low temperature range, becomes slightly cooler than air temperature due to heat losses by radiation to a cool sky. By construction, conductive and convective heat losses are equal for all the spheres when they are at the same temperature. The temperature of the warmest sphere is measured and heat is added to the cooler spheres to bring them to the same temperature. This heat is measured and serves to separate the radiation absorbed from the environment from the radiation lost to the environment. For example, at equilibrium, heat gained by the black sphere from the sun equals heat lost by the sphere to the environment through conduction along the support, convection losses to the cooler ambient air and radiation losses to the cooler areas of the environment. Thus, as shown in the following equation, the total radiation from the sun, R , times the emissivity of the sphere in the visible, is equal to the Stefan-Boltzmann low temperature radiation exchange plus convection and conduction heat losses. For the black sphere:

$$R \epsilon_{bv} = S_o \epsilon_{bi} \epsilon_{si} (T_b^4 - T_s^4) + C + D \quad \text{equation 1}$$

where

- R = total radiation from the sun incident upon the sphere
- ϵ_{bv} = emissivity of the black sphere in the visible
- S_o = Stefan-Boltzmann radiation constant
- ϵ_{bi} = emissivity of the black sphere in the infrared
- ϵ_{si} = emissivity of the surroundings in the infrared

T_b = temperature of black sphere
 T_s = radiant temperature of surroundings
 C = convection heat losses
 D = conduction heat losses

Similar equations may be written for the white and the polished spheres by adding the term for heat input to the total radiation.

For the white sphere:

$$I_w + R \epsilon_{wv} = S_o \epsilon_{wi} \epsilon_{si} (T_w^4 - T_s^4) + C + D \quad \text{equation 2}$$

For the polished sphere:

$$I_p + R \epsilon_{pv} = S_o \epsilon_{pi} \epsilon_{si} (T_p^4 - T_s^4) + C + D \quad \text{equation 3}$$

It is a simple matter then to solve the equations simultaneously to find the total radiation, R , and the average temperature of the surroundings, T_s . By shading the spheres from the direct solar radiation and repeating the heat balance measurements, the total radiation in the shade may be measured. The difference between this quantity and the total radiation in the sun is then a measure of the direct solar radiation.

Thus, all the measurements required for defining the radiant environment may be obtained in 5 to 15 minutes given reasonable stability of the wind and cloud formations. Violent wind and cloud changes render it difficult, and sometimes impossible, to obtain a reading because of the difficulty of rapid manual adjustment of heat balance inputs. It has been suggested to the engineers (17) that a task worthy of their undertaking would be the development of a servo-operated Panradiometer for remarkable results can be achieved quickly under favorable conditions. The accuracy of the instrument is good as indicated by the data in Figures 6, 7, and 8. Figure 6 shows the comparison of wall temperature as ascertained by the Panradiometer in a temperature controlled walk-in chamber with the temperature of the walls as indicated by thermocouples. It is seen that, in still air, the measurements are accurate to $\pm 0.1^\circ\text{C}$ which is the limiting accuracy of the calibration of the thermocouples. With turbulence produced by an

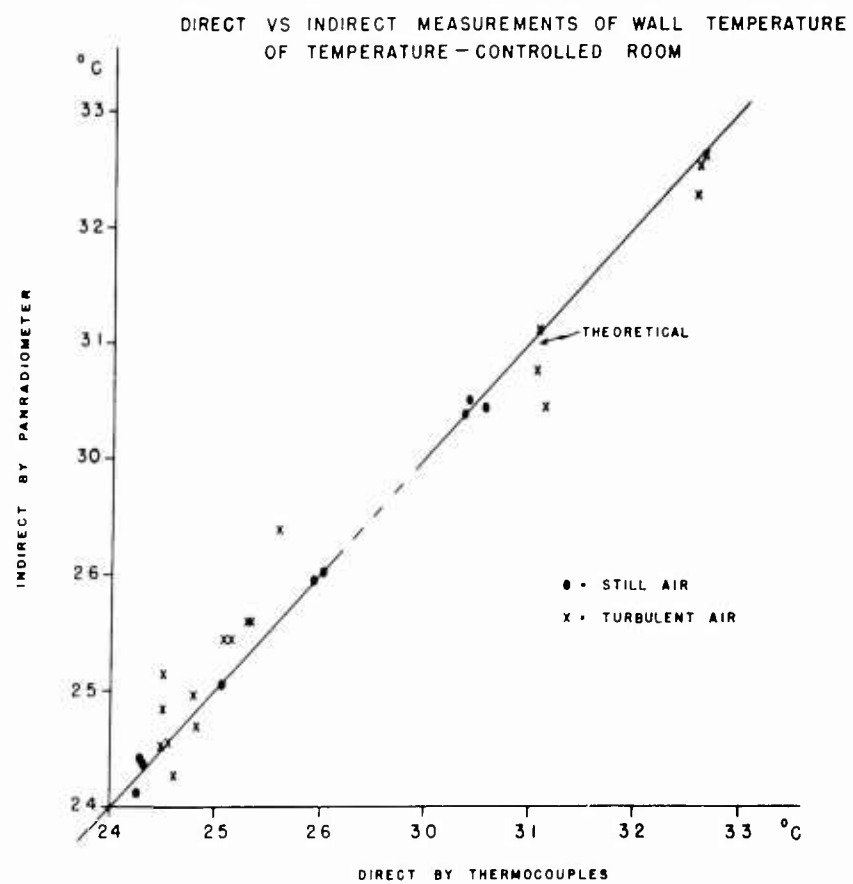


Figure 6. Panradiometer measurements of wall temperature compared with thermocouple measurements.

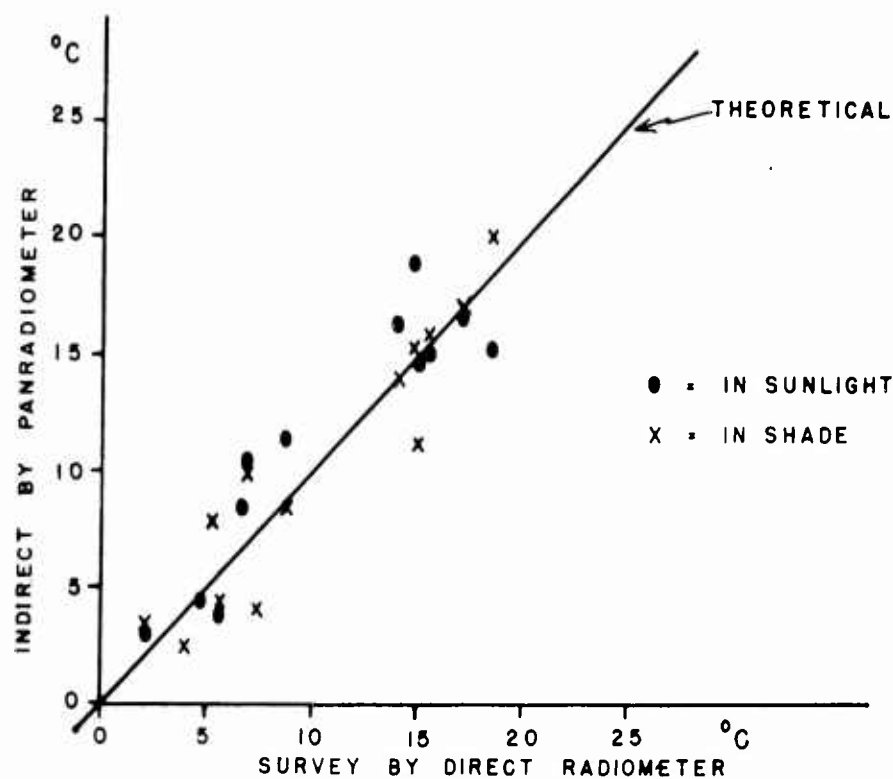


Figure 7. Panradiometer measurements of the radiant temperature of the surroundings compared with direct survey.

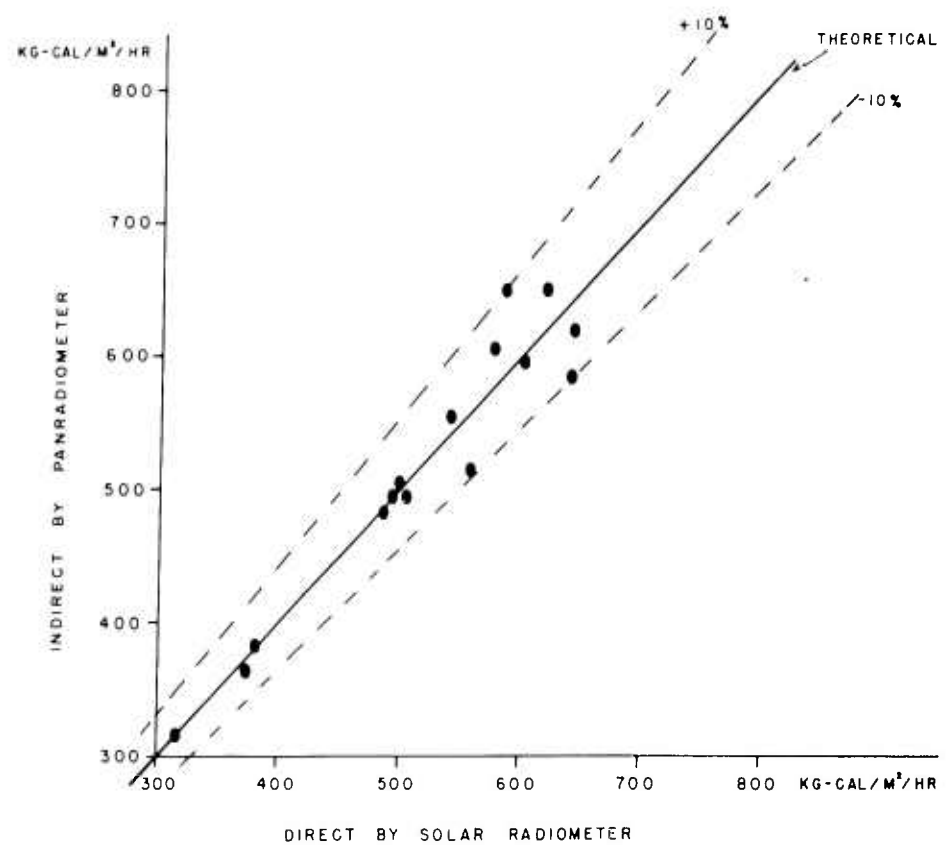


Figure 8. Panradiometer measurements of direct solar radiation compared with direct measurements.

electric fan directed at the spheres, the scatter was increased to $\pm 0.3^{\circ}\text{C}$. Figure 7 shows the comparison of measurements of the outdoor surroundings in sun and shade as made with the Panradiometer, and by direct survey with the Thermoradiometer or the Thermistor Radiometer described earlier. The average deviation of the mean is about $\pm 1.8^{\circ}\text{C}$. Finally, in order to check on the accuracy of the Panradiometer measurements of direct solar radiation, an automatically tracking radiometer was set up and directed at the sun. The output of this instrument was recorded continuously and these readings were then compared with those obtained on the Panradiometer at any given time. The results are shown in Figure 8. It is seen that the maximum deviation of the mean is $\pm 10\%$ and the average deviation is 4% .

APPLICATIONS

With the instruments described, measurements were made in New York City in all seasons, in Nome and Fairbanks, Alaska in the summer and Fairbanks in the winter (18). Duplicate instruments were made for the Office of the Quartermaster General and a group led by Norman Sissenwine collected data in Death Valley during the hottest part of one summer (19). Isolated readings have been made in other localities from time to time but such observations are of little use without the support of a body of systematic data. Indoors, the instruments were used to determine the heat load incident on infants exposed to brilliant operating lights during surgery.

Outdoors

Climatic physical data are related to biology by casting them in a form whereby the physiological knowledge obtained in controlled laboratory environmental chambers becomes applicable to the naturally occurring climatic situation. One physiologically important quantity so used, shown in equation 4 is the radiant heat load (16).

$$H_m = \left[\frac{R_o}{4} + \frac{(\alpha + \gamma) R_o}{2} \right] \epsilon_{mv} - \epsilon_{mi} S_o (T_m^4 - T_s^4) \quad \text{equation 4}$$

solar contribution low temperature exchange

where

H_m = radiant heat load

R_o = direct solar radiation

$$\begin{aligned}
(a + \gamma) R_o &= \text{scattered + reflected solar radiation} \\
\epsilon_{mv} &= \text{emissivity of man in the visible (0.5)} \\
\epsilon_{mi} &= \text{emissivity of man in the infrared (1.0)} \\
S_o &= \text{Stefan-Boltzmann radiation constant} \\
T_m &= \text{surface temperature of the man} \\
T_s &= \text{radiant temperature of the surroundings}
\end{aligned}$$

This quantity depends upon the total solar radiation absorbed by the man, minus the heat he is able to lose by radiation to his surroundings. It is computed from the measured values of total solar radiation which includes reflected and scattered, as well as the direct radiation, and the radiant temperature of the surroundings averaging that of the sky, ground, terrestrial objects and any other sinks or sources of low temperature radiation in the vicinity. The surface temperature of the man and the emissivity of his surface may be measured but can be reliably assumed for various conditions.

A second parameter of importance, shown in equation 5 is the operative temperature, a concept developed at the Pierce Laboratory of Hygiene (7) and presented at the 2nd Temperature Symposium in 1939.

$$T_o = \frac{K_r (T_w) + K_c (T_a)}{K_r + K_c} \quad \text{equation 5}$$

where

$$\begin{aligned}
T_o &= \text{operative temperature} \\
K_r &= \text{radiation "constant"} \\
T_w &= \text{radiant wall temperature} \\
K_c &= \text{convection "constant"} \\
T_a &= \text{air temperature}
\end{aligned}$$

This system combines the effect of radiation and convection weighted properly to represent their respective physical influences on the body in accordance with Newton's Cooling Law. It constitutes a temperature scale

which serves to indicate, with respect to the nude or lightly clothed body, the physiological thermoregulatory processes brought into action by the net effect of radiation, air temperature, and air movement. Thus, at operative temperatures below 29°C , the body is cooling. Between 29°C and 31°C , vasomotor regulation maintains heat balance while, above 31°C , thermal balance is maintained by evaporative regulation. This scale provides an important bridge between the physical features of the outdoor climate and their physiological consequences.

Table I presents data to illustrate this correlation of physical features and physiological response: on the left appear the data on season and region; in the center, the physical description, the physiologically significant values, and the response of the body; and, on the right, the action required to maintain thermal balance. It may be pointed out, for instance, that in the New York City summer, with a moderately high solar radiation intensity and moderately high temperature of air and surroundings, the radiant heat load is also moderate; with an ordinary wind speed, the operative temperature occurs at the upper limit of the zone of vasomotor regulation and no additional action is required to maintain thermal balance. However, in Fairbanks, with a higher solar radiation, but cool air and surroundings, the radiant heat load is almost zero; and with an unusually high wind speed for this location, the operative temperature falls in the near portion of the cooling zone requiring slightly increased metabolic output or additional clothing to maintain thermal equilibrium. In the desert summer, with a solar intensity about equal to that of New York City which lies at about the same latitude, the air and surroundings are hot, the heat load very high, and the operative temperature so high that shelter is indicated. The winter analyses are equally revealing. All radiant heat loads are negative and the operative temperatures fall far out in the cooling range, particularly in the Arctic night.

Figure 9 presents data selected from actual observations to point up specific effects. Thus, times were chosen when the solar radiation intensity was the same in all three regions so that the solar radiant contribution was equal throughout. Similarly, the wind velocity was the same and convective heat loss differences depended solely on temperature differences, not on velocity differences. Quite striking effects are seen. The effective sky temperature in the Arctic is below zero, while it is well above zero and approximately equal in New York City and in Death Valley. The air temperature is greatly different in the three environments while the ground temperature reflects the influence of the solar radiation by being above air temperature, and the influence of the relatively low sky temperatures by being not greatly above air temperature, except in the hot desert. The effect of

TABLE I
BIOClimATOLOGICAL DATA FROM THREE LOCALITIES.

CHARACTERISTICS

← PHYSICAL ————— * ————— PHYSIOLOGICAL →

Season	Locale	R_o Kcal/m ² hr	$(\alpha + \gamma) R_o$ Kcal/m ² hr	T_a °C	T_s °C	Wind Vel. mph	H_m Kcal/m ² hr	T_o °C	Thermal Effect	Action To Maintain Thermal Balance
Summer	New York City	582	92	26.4	31.3	7.5	+80	31.0	neutral	none
Summer	Fairbanks	794	103	20.3	9.2	11.0	-1	23.7	cooling	slight increase metab. or insul.
Summer	Death Valley	588	147	46.1	47.4	3.1	+192	53.0	heating	shelter
Winter	New York City	506	21	3.8	-4.0	5.0	-73	6.8	cooling	increase metab. and insul.
Winter day	Fairbanks	236	53	-31.5	-37.2	1.2	-154	-26.0	cooling	shelter
Winter night	Fairbanks	0	0	-30.0	-42.0	3.4	-259	-33.2	cooling	shelter

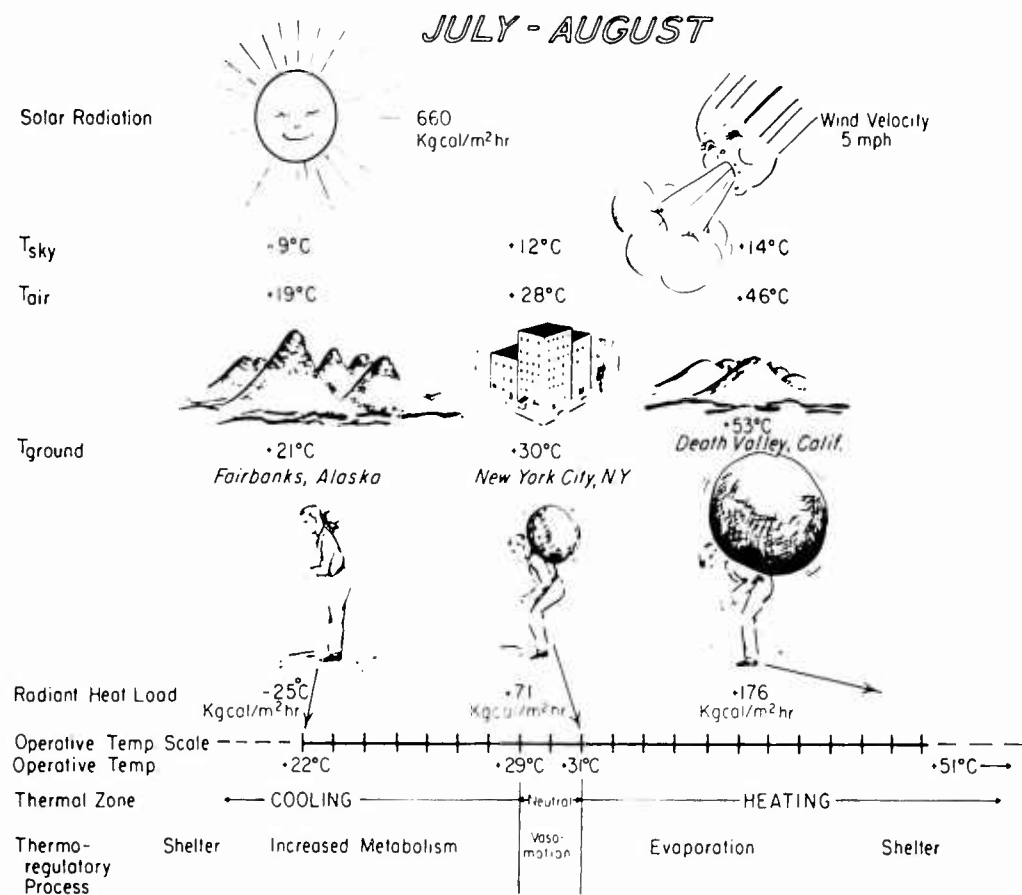


Figure 9. Selected data from three localities to show interaction of bioclimatological components.

the temperature of the sky and ground in providing sinks and sources of low temperature radiation is reflected in the radiant heat load. Remembering that the solar contribution is the same in all three environments, it is seen that the radiant heat load progresses from slightly negative in the Arctic desert to positive in the city and greatly positive in Death Valley. Thus, the cool surroundings of the Arctic region provide a radiation sink while the hot surroundings of the temperate zone desert act as an additional source of radiation. With respect to the man, the net result of all the factors shown may be expressed in terms of the operative temperature. It is seen that the man in Fairbanks has a light radiant heat load to contend with and is exposed to an operative temperature of 22°C , somewhat below the neutral zone of thermal balance. Cooling proceeds by radiation and convection and is easily controlled by light clothing. This is a very pleasant environment. The man in New York City has a fairly appreciable radiant heat load to carry but still finds himself, by virtue of some losses to the surroundings, in the region of the upper limit of the neutral thermal zone where vasomotor changes alone suffice to maintain thermal balance. The man in Death Valley has the greatest burden for his solar load is increased by radiation from the surroundings whose temperature exceeds his own surface temperature. The operative temperature is extremely high and indicates that shelter is required to protect him against the body heating which evaporation alone is insufficient to prevent.

The possibilities suggested here need no belaboring. It is quite obvious that once the extremes and the mean values for the physical parameters have been established by systematic measurement, it is a relatively simple matter to draw up charts to indicate the amount of insulation or heat, or clothing, or whatever may be required to maintain life and comfort in any given environment. The importance of such an approach is readily apparent in military logistics where it might well prevent tragedies brought about by the right clothing in the wrong place. There are additional implications of importance to the fabric construction and design field but there is little point in expounding these possibilities before the time that systematic bioclimatological data and analyses are available.

Indoors

With respect to the indoor environment, the sort of specialized information that can be obtained from radiometric evaluations is suggested by the following data (20). They are taken from a study of the heating effect of operating lights focussed on the operating field during surgery in infants and young children. The Panradiometer was substituted for the patient on

the operating table and measurements were taken over periods of time equivalent to those required for various operations. Table II presents some of the results: The data at zero time relate to an empty room with one operating light on. The radiation effective on the "patient", with air and surrounding temperatures at a warm but not excessive level, is such that the radiant heat load is negative and the operative temperature is within the neutral zone. Thirty minutes later it is obvious that the room is gradually heating up, the radiant heat loss is diminishing and the operative temperature is climbing toward the zone of evaporative temperature regulation. With the addition of two more operating lights turned on after 60 minutes, the radiation level almost doubles, all temperatures increase significantly, the heat load becomes positive, and the operative temperature approaches the limit of evaporative regulation ability, particularly that of the immature regulatory system of the infant. From these data, it was computed that with the three lights on, the rise in body temperature of a one-year-old would be 2.4°C/hr. , of a five-year-old, 1.7°C/hr. Thus, under these conditions, which were neither unusual nor extreme as compared with reality, a five-year-old could tolerate this exposure for about 2 hours while a one-year-old might withstand it for only one hour without fatal consequences.

SUMMARY OF RESULTS

In summary it may be said that the examples here presented demonstrate that the data supplied by use of the Panradiometer and the Thermistor Radiometer have pertinent application both indoors and out wherever radiant heat exchange is important. The importance of such exchange has been touched upon with respect to locations in the temperate and Arctic zones, and desert climates. Radiation exchange is perhaps less important in the tropical jungles where humidity may be the dominant feature or in constantly windswept localities where the operative temperature is essentially the air temperature. However, until such times as data become available through observation, the relative importance of these factors in any given environment can only be surmised.

In this report only a few of the salient features of the environment that may be ascertained with these instruments have been illustrated. It was not shown, for instance, how the sky, air, and ground temperatures equalize when a heavy overcast prevails or how cloud formations affect the thermal balance (16, 18), nor even the extremes or means of any of the thermal variations in any one place or season. The importance of the bioclimatological analysis in pursuits such as cattle-raising (21) has not

TABLE II
MEASUREMENTS OF RADIANT HEAT LOAD AND OPERATIVE TEMPERATURE
INDOORS UNDER OPERATING LIGHTS.

Time (min)	R Kcal/m ² hr	T _a °C	T _s °C	T _w °C	H _m Kcal/m ² hr	T _o °C	Thermal Reg. Zone
0	35.1	27.5	27.2	29.8	-18.7	29.2	vasomotor
30	52.7	29.3	27.1	31.0	-11.9	30.2	vasomotor
60	93.0	32.3	29.3	38.4	+25.4	36.2	evaporative
75	102.2	33.3	29.4	38.4	+25.5	36.8	evaporative

been touched upon here but its importance is obvious and the field too broad to include in this report. Some of the foregoing points have been discussed in the publications referenced but, again, the wealth of data required for comprehensive analyses yet remains to be obtained. In conclusion it may be said that the instruments and the methods described here are of proven value in providing bioclimatological measurements. They could be adapted to automatic operation which would greatly enhance their value. Should this step be taken, the routine collection and processing of complete sets of data would become entirely feasible in all regions of economic, military, and habitation importance throughout the world.

REFERENCES

1. Hill, T. Kata-thermometer in studies of body heat and efficiency. Med. Res. Council (Brit.), Special Report, Ser 73, 48, 1923-b.
2. Dufton, A. F. The Eupathoscope. Dep. Sci. Ind. Research (Brit.), Bld. Research, Tech. Paper No. 15, 1932.
3. Vernon, H. M. Determination of single index of atmospheric conditions in relation to physiologic effects. J. Ind. Hyg. & Toxicol. 14: 328-338, Nov 1932.
4. Mackey, C. O. and L. T. Wright. Skin-air temperature — a new instrument. Am. Soc. Heating & Ventilating Engrs., Journal Section, Heating, Piping and Air Conditioning, Vol. 18, 107-111, May 1946.
5. Winslow, C. - E. A. and L. Greenberg. The Thermo-integrator — new instrument for observation of thermal interchanges. Am. Soc. Heating & Ventilating Engrs., Trans. 41-43, Vol. 7, No. 1, 41-43, Jan 1935.
6. Hardy, J. D., E. F. DuBois, and G. F. Soderstrom. The technique of measuring radiation and convection. Clin. Cal., No. 49, J. Nutrition 15, 461, 1938.
7. Winslow, C. - E. A. Man's heat exchanges with his thermal environment. In Temperature: Its Measurement and Control in Science and Industry, Reinhold Pub. Corp., New York, 1941, p. 509.
8. Hardy, J. D. and E. F. DuBois. The significance of the average temperature of the skin. In Temperature: Its Measurement and Control in Science and Industry, Reinhold Pub. Corp., New York, 1941, p. 537.
9. Gagge, A. P. Standard operative temperature, a single measure of the combined effect of radiant temperature, of ambient air temperature, and of air movement on the human body. In Temperature: Its Measurement and Control in Science and Industry, Reinhold Pub. Corp., New York, 1941, p. 544.
10. Elsasser, W. M. Heat transfer by infrared radiation in the atmosphere, Harvard Met. Stud., 6, 1912.
11. Haurwitz, B. Dynamic Meteorology, Radiation, McGraw-Hill Book Co., Inc., New York, 1951, p. 85.

12. Richards, R. H., A. M. Stoll, and J. D. Hardy. The Panradiometer: An absolute measuring instrument for environmental radiation. *Rev. Sci. Inst.* 22, 925, 1951.
13. Stoll, A. M. and J. D. Hardy. A method of measuring radiant temperatures of the environment. *J. Appl. Physiol.* 5, No. 3, 117, 1952.
14. Hardy, J. D. The radiation of heat from the human body. I. An instrument for measuring the radiation and surface temperature of the skin. *J. Clin. Invest.* 13, 593, 1934.
15. Stoll, A. M. A wide-range thermistor radiometer for the measurement of skin temperature and environmental radiant temperatures. *Rev. Sci. Inst.* 25, No. 2, 184, 1954.
16. Hardy, J. D. and A. M. Stoll. Measurement of radiant heat load on man in summer and winter Alaskan climates. *J. Appl. Physiol.* 7, No. 2, 1954.
17. Stoll, A. M., J. D. Hardy, and C. H. Richards. The servo-operated Panradiometer, an engineering need in physiological heat transfer studies. Heat Transfer Division, Semi-annual meeting of Amer. Soc. of Mech. Eng., June 1957.
18. Stoll, A. M. and J. D. Hardy. Thermal radiation measurements in summer and winter Alaskan climates. *Trans. Am. Geophysical Union* 36, No. 2, 213, 1955.
19. Sissenwine, N., R. Ansteg, and P. Meigs. Studies on clothing for hot environments. Environmental Protection Report 178, Office of Quartermaster General, Vol. 5, Dept. Army, p. 58, 1951.
20. Stoll, A. M. Unpublished data.
21. Brody, S. Temperature factors in animal production. In *Temperature: Its Measurement and Control in Science and Industry*, Reinhold Pub. Corp., New York, 1941, p. 462.

<p>1. Report NADC-MA-6108 2. BuMed Subtask MR005, 15-2002.1</p>	<p>1. Report NADC-MA-6108 2. BuMed Subtask MR005, 15-2002.1</p>	<p>1. Report NADC-MA-6108 2. BuMed Subtask MR005, 15-2002.1</p>
<p>1. Report NADC-MA-6108 2. BuMed Subtask MR005, 15-2002.1</p>	<p>1. Report NADC-MA-6108 2. BuMed Subtask MR005, 15-2002.1</p>	<p>1. Report NADC-MA-6108 2. BuMed Subtask MR005, 15-2002.1</p>

individual. The design of this instrument takes advantage of the fact that about 99% of the solar radiation lies at wavelengths less than 3μ and about the same proportion of the radiation from man to his surroundings lies at wavelengths longer than 4μ . Thus, by utilization of heat detectors of different emissivities, the high temperature radiation is separated from the low temperature radiation. In brief, the instrument embodies three detectors which consist of hollow spheres equipped with thermocouples for measuring their temperatures and internal heaters for adjusting their temperatures. When all spheres are brought to the temperature of the warmest sphere in a given environment, the amount of heat required to maintain this balance is an accurate measure of the environmental heat exchange from which various temperature and radiation terms are derived. Wind temperature and velocity are measured by means of a fourth sphere. A few representative natural environments have been evaluated with these two instruments. Illustrative of the sort of information derivable are the comparisons of radiant heat loads and operative temperatures measured in midsummer in the hot desert of Death Valley, in the arid Alaskan interior at Fairbanks, and in the heart of New York City. It is seen that the main difference between a stressfully hot environment and a thermally comfortable one was not due to a decreased solar intensity in Alaska, as might be supposed, for the Panradiometer measurements showed that some of the highest solar intensities occurred there. Instead, the cooler environment despite equivalent solar radiation, was shown by the Thermistor Radiometer measurements to be due primarily to the cool sky which constituted a sink for the radiation from the earth and the man, contributing both directly and indirectly to reduction of the radiant heat load. In the indoor environment, measurements of radiant heat load made with these instruments provided concrete evidence of the need for air-conditioning in operating rooms for infants and small children.

individual. The design of this instrument takes advantage of the fact that about 99% of the solar radiation lies at wavelengths less than 3μ and about the same proportion of the radiation from man to his surroundings lies at wavelengths longer than 4μ . Thus, by utilization of heat detectors of different emissivities, the high temperature radiation is separated from the low temperature radiation. In brief, the instrument embodies three detectors which consist of hollow spheres equipped with thermocouples for measuring their temperatures and internal heaters for adjusting their temperatures. When all spheres are brought to the temperature of the warmest sphere in a given environment, the amount of heat required to maintain this balance is an accurate measure of the environmental heat exchange from which various temperature and radiation terms are derived. Wind temperature and velocity are measured by means of a fourth sphere. A few representative natural environments have been evaluated with these two instruments. Illustrative of the sort of information derivable are the comparisons of radiant heat loads and operative temperatures measured in midsummer in the hot desert of Death Valley, in the arid Alaskan interior at Fairbanks, and in the heart of New York City. It is seen that the main difference between a stressfully hot environment and a thermally comfortable one was not due to a decreased solar intensity in Alaska, as might be supposed, for the Panradiometer measurements showed that some of the highest solar intensities occurred there. Instead, the cooler environment despite equivalent solar radiation, was shown by the Thermistor Radiometer measurements to be due primarily to the cool sky which constituted a sink for the radiation from the earth and the man, contributing both directly and indirectly to reduction of the radiant heat load. In the indoor environment, measurements of radiant heat load made with these instruments provided concrete evidence of the need for air-conditioning in operating rooms for infants and small children.

individual. The design of this instrument takes advantage of the fact that about 99% of the solar radiation lies at wavelengths less than 3μ and about the same proportion of the radiation from man to his surroundings lies at wavelengths longer than 4μ . Thus, by utilization of heat detectors of different emissivities, the high temperature radiation is separated from the low temperature radiation. In brief, the instrument embodies three detectors which consist of hollow spheres equipped with thermocouples for measuring their temperatures and internal heaters for adjusting their temperatures. When all spheres are brought to the temperature of the warmest sphere in a given environment, the amount of heat required to maintain this balance is an accurate measure of the environmental heat exchange from which various temperature and radiation terms are derived. Wind temperature and velocity are measured by means of a fourth sphere. A few representative natural environments have been evaluated with these two instruments. Illustrative of the sort of information derivable are the comparisons of radiant heat loads and operative temperatures measured in midsummer in the hot desert of Death Valley, in the arid Alaskan interior at Fairbanks, and in the heart of New York City. It is seen that the main difference between a stressfully hot environment and a thermally comfortable one was not due to a decreased solar intensity in Alaska, as might be supposed, for the Panradiometer measurements showed that some of the highest solar intensities occurred there. Instead, the cooler environment despite equivalent solar radiation, was shown by the Thermistor Radiometer measurements to be due primarily to the cool sky which constituted a sink for the radiation from the earth and the man, contributing both directly and indirectly to reduction of the radiant heat load. In the indoor environment, measurements of radiant heat load made with these instruments provided concrete evidence of the need for air-conditioning in operating rooms for infants and small children.

individual. The design of this instrument takes advantage of the fact that about 99% of the solar radiation lies at wavelengths less than 3μ and about the same proportion of the radiation from man to his surroundings lies at wavelengths longer than 4μ . Thus, by utilization of heat detectors of different emissivities, the high temperature radiation is separated from the low temperature radiation. In brief, the instrument embodies three detectors which consist of hollow spheres equipped with thermocouples for measuring their temperatures and internal heaters for adjusting their temperatures. When all spheres are brought to the temperature of the warmest sphere in a given environment, the amount of heat required to maintain this balance is an accurate measure of the environmental heat exchange from which various temperature and radiation terms are derived. Wind temperature and velocity are measured by means of a fourth sphere. A few representative natural environments have been evaluated with these two instruments. Illustrative of the sort of information derivable are the comparisons of radiant heat loads and operative temperatures measured in midsummer in the hot desert of Death Valley, in the arid Alaskan interior at Fairbanks, and in the heart of New York City. It is seen that the main difference between a stressfully hot environment and a thermally comfortable one was not due to a decreased solar intensity in Alaska, as might be supposed, for the Panradiometer measurements showed that some of the highest solar intensities occurred there. Instead, the cooler environment despite equivalent solar radiation, was shown by the Thermistor Radiometer measurements to be due primarily to the cool sky which constituted a sink for the radiation from the earth and the man, contributing both directly and indirectly to reduction of the radiant heat load. In the indoor environment, measurements of radiant heat load made with these instruments provided concrete evidence of the need for air-conditioning in operating rooms for infants and small children.